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OPEN PROBLEMS AND RESEARCH PERSPECTIVES FOR IRRIGATION CHANNELS

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1. **Introduction: Management of canal networks at the age of information technology.** With the miniaturization of sensors and their decreasing costs, the paradigm of instrumentation of the built infrastructure and the environment has now been underway for several years, leading to numerous successful and sometimes spectacular realizations such as the instrumentation of the Golden Gate with wireless sensors a few years ago. The convergence of communication, control and sensing on numerous platforms including multi-media platforms has enabled engineers to augment physical infrastructure systems with an information layer, capable of real-time monitoring, with particular success in the health monitoring community. This paradigm has reached a level of maturity, revealed by the emergence of numerous technologies usable to monitor the built infrastructure. *Supervisory Control And Data Acquisition* (SCADA) systems are a perfect example of such infrastructure, which integrate sensing, communication and control. In the context of management of irrigation networks, the impact of this technology on the control of such systems has the potential of significantly improving efficiency of operations.

The idea of "closing the loop" in large scale infrastructure systems is not new, in fact in water management systems such as estuarine environments in the US, State authorities have talked about it for now more than a decade, for example in California. In Vietnam, farmers already operate gates on tidal timescales to manage irrigation properly for rice and shrimps. The "last mile" in enabling one to "close the loop" (at least in the case of estuarine environments is the capability of using sensor data in real time to integrate accurate hydrodynamic features of the system which directly intervene in the feedback loop.

2. **Contributions.** This special issue of *Networks and Heterogeneous Media* assembles a collection of articles linked with a workshop on"Irrigation channels and related problems" organized in Maiori, Italy, October 2-4, 2008. The workshop involved experts with fields which included sensor hardware manufacturing, estimation and control, hydrodynamic modeling and control and optimization of partial differential equations. The goal of the workshop was to cross-fertilize ideas between these different fields with the irrigation application in mind. This special issue of *Networks and Heterogeneous Media* includes articles by some of the presenters on their respective topics of expertise. The complete list, in alphabetical order, is the following:

2000 *Mathematics Subject Classification.* Primary: 35L65, 35L50; Secondary: 76B75.
Key words and phrases. Irrigation channels.

- G. Bastin, J.-M. Coron, B. d'Andrea-Novel, *On Lyapunov stability of linearised Saint-Venant equations for a sloping channel.*
- N. Bedjaoui, E. Weyer, G. Bastin, *Methods for the localization of a leak in open water channels.*
- G. Besancon, D. Georges, Z. Benayache, *Towards nonlinear delay-based control for convection-like distributed systems: the example of water flow control in open channel systems.*
- J.B. De Sousa, B. Maciel, F. Lobo Pereira, *Sensor systems on networked vehicles.*
- V. Dos Santos, Y. Le Gorrec, B. Maschke, *A Hamiltonian perspective to the stabilization of systems of two conservation laws.*
- D. Georges, *Infinite-dimensional nonlinear predictive control design for open-channel hydraulic systems.*
- P. Goatin, *Traffic flow models with phase-transitions on road networks.*
- J.M. Lemos, F. Machado, N. Nogueira, L. Rato, M. Rijo, *Adaptive and non-adaptive model predictive control of an irrigation channel.*
- X. Litrico, V. Fromion, *Modal decomposition of linearized open channel flow.*
- R. R. Negenborn, P.-J. van Overloop, T. Keviczky, B. De Schutter, *Distributed model predictive control of irrigation canals.*
- T.-T. Pham, T. Green, J. Chen, P. Truong, A. Vaidya, L. Bushnell, *A Salinity Sensor System for Estuary Studies.*
- C. Prieur, *Control of systems of conservation laws with boundary errors.*
- I.S. Strub, J. Percelay, O.-P. Tossavainen, A.M. Bayen, *Comparison of two data assimilation algorithms for shallow water flows.*

The contributions to the special issue can be broadly classified into three main domains:

1. Articles dealing with the *modeling* of networks. The paper by X. Litrico and V. Fromion and the one by P. Goatin fall into this category.
2. Articles dealing with the *control* of flow in networks. The contributions range from finite dimensional nonlinear control (paper by G. Besancon, D. Georges and Z. Benayache), predictive adaptive control (J. Lemos, Machado, Nogueira, L. Rato, M. Rijo), predictive control (one paper by R. Negenborn, P.-J. van Overloop, T. Keviczky and B. De Schutter and one paper by D. Georges) to infinite dimensional control (three papers, one by C. Prieur, one by V. Dos Santos, Y. Le Gorrec, B. Maschke, and one by G. Bastin, J.-M. Coron and B. d'Andrea-Novel).
3. Articles dealing with the *measurement and estimation* of flow in networks. This includes four papers, one by T.-T. Pham, T. Green, J. Chen, P. Truong, A. Vaidya and L. Bushnell, one by N. Bedjaoui, E. Weyer and G. Bastin, one by De Sousa, Maciel and Lobo Pereira, and one by Strub, Percelay, Tossavainen and Bayen.

During the workshop, several promising directions have been identified by the participants, with the potential of integration of the different ideas produced by the conversations. The subsequent sections summarize the items which were discussed.

3. **Open problems.**

In light of the conversations at the workshop, and in particular during the round table, the following open problems were identified. Most of them are cross-disciplinary by nature and span most of the topics covered in the workshop.

1. *Operational problems:* most applications covered in the workshop seem to have been motivated by one of the following operational problems: monitoring, surveillance, optimal management of resources, or control of the system.
2. *Tools:* several tools have been identified as appropriate to implement these operations in the field. The tools range from sensor network systems (such as SCADA or wireless sensors) to mobile robotics platforms. The issue of manufacturing costs of sensors was judged of importance, since typically water irrigation networks span large areas and require numerous monitoring stations.
3. *Phenomenon driven control:* one key item which was identified is that the control schemes devised to achieve operational needs with the tools available need to be phenomenon driven, which requires accurate modeling of the hydrodynamic systems of interest.
4. *Capabilities:* as a corollary to the accurate modeling required for operations, data assimilation and real-time computing appear as two main capabilities needed for operations, which are directly linked to the models of interest. Particular attention was paid to data assimilation and inverse modeling in the context of estimation.
5. *Models:* numerous models were used by the participants to the workshop, with diverse levels of complexity (from three dimensional Navier-Stokes equations to delayed ODE models). Clear tradeoffs need to be established between accuracy and efficiency in the treatment of the models, which is reflected by the various models used in the different articles presented in this issue.
6. *Complexity:* numerous examples presented in the workshop included networks, which appears as a major challenge for this area. Beyond the modeling challenges associated to networked aspects of hydrodynamics, the issue raised by the use of SCADA systems also led to the consideration of controlling over networks, which is an additional challenge.
7. *Mathematical challenges:* the emergence of new theories such as hybrid systems led to interesting open questions such as the coupling of PDEs and hybrid systems, a set of problem for which no framework was generically developed up to date. Several of the articles presented tackled some very theoretical questions associated with the proper mathematical definition of the solutions to the considered problems, linked to the fact that the stabilization of the corresponding equations have to be handled in a specific context.
8. *Design:* finally, the problem of design was considered of interest, specifically in the context of network design. Designing control policies for operations can be thought of as designing the network itself, when it is not only driven by geometry, but also by control points and corresponding operations.

The cross discipline issues emerging in the field of irrigation networks can be summarized by the following picture Figure 1.

4. **Mathematical challenges.** In this section we illustrate in more details some specific mathematical challenges posed by the discussions illustrated above.

1. **Theory of irrigation networks and hydrodynamic modeling.** Some papers were devoted to irrigation networks proposing some choice for dynamics at nodes. In particular, using the Saint Venant equations as hydrodynamic model and asking for conservation of mass, two different approaches are the following:

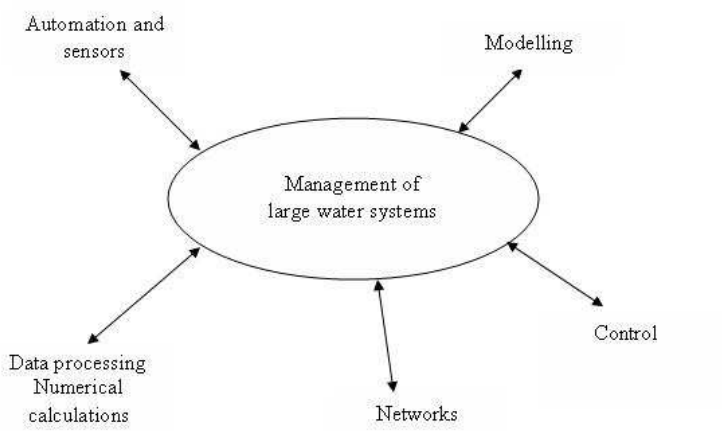

FIGURE 1. Scheme of disciplines involved in the management of large water systems.

- Impose equal energy from every channel (or impose equality between the sums over entering and exiting channels);
- Impose equality of water levels.

In both cases a complete description of equilibria is not available. The most interesting cases are those of bifurcations and merging: in the first case there is one entering and two exiting channels, while the opposite for the second case. Trivial equilibria are easily found, however there is no proof of existence of equilibria in generic case.

Various authors treated the case of sequence of channels, which corresponds to the case of nodes with one entering and one exiting channels. If some control is available at nodes, then it is possible (under suitable and realistic conditions) to avoid the formation of singularities such as shocks. However, it appears quite difficult to avoid such discontinuities in case of complicate networks with only partial control at nodes.

2. **Control of waste water over large distribution systems.** As mentioned in the previous point there are good results for control at nodes in case of cascades of channels. However the precise problem of water wasting is not completely solved. One of the key point is the fact that wastes may occur almost everywhere along the network, while control is available (at most) at nodes. This implies that the system has serious limitation for controllability properties and in general presents delays in the control actuation. Also, the first issue to be addressed is the one of waste localization. During the Workshop some results in this direction were presented by N. Bedjaoui. Mathematically this is an inverse problem.
3. **Design optimization of irrigation network topologies.** The optimization of the shape of an irrigation network is a quite unexplored issue, which

asks for new mathematical tools. Such problem may arise at the level of projecting of irrigation networks, however it may be useful also in case of smaller adjustments, such as the opening of a new link along the network or the closure of an already existing ones. Other application domains, as traffic control, shows many interesting phenomena, including the well known Baess paradox. Some results were obtained in the math community using optimal transport theory. However, such results hardly reach a maturity at the level of computational methods, in order to allow for real applications. Therefore completely new tools or the adaptation of optimal transport to water channels case are desirable.

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